166 GHZ ICE SCATTERING SIGNAL IN SNOWFALL EVENTS OVER OCEAN

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ABSTRACT

Snowfall retrieval algorithms for spaceborne passive microwave (PMW) sensors have been developed and refined in recent years, but many complicating issues still affect their accuracy and reliability. Previous work showed that the Global Precipitation Measurement (GPM) mission Goddard PROFiling (GPROF) algorithm snowfall retrieval performance strongly depends on the snowfall type. In particular, PMW-based detection of shallow cumuliform snowfall (SCS), which accounts for 36%-70% of global snowfall frequency, can be very challenging. The snowfall scattering signal can be contaminated by the background surface or supercooled cloud liquid water emission. A scattering index (SI) approach that exploits the GPM Microwave Imager (GMI) dual-polarization 166 GHz channels is developed to analyze its behavior in presence of SCS over ocean. Case studies show that, compared to the SI at 89 GHz, it can isolate the SCS snowfall scattering signal in extremely dry conditions. Some issues are still observed in presence of supercooled liquid water.

Index Terms— Snowfall, Scattering Index, Passive Microwave, GPM

1. INTRODUCTION

Falling snow is a key component for the global atmospheric, hydrological and energy cycles and profoundly affects human activities. Falling snow retrievals derived from space-based observations represent the best current capability to evaluate it globally. Precipitation retrieval algorithms have been improved over time and their accuracy and reliability are becoming increasingly more important to study the Earth's energy and radiation budgets. Unfortunately, snowfall retrievals are still affected by large uncertainties. In particular, some type of snowfall, such as shallow cumuliform snowfall (SCS) events, are extremely difficult to detect and in many cases are completely missed [1].

Kulie et al. [2][3] presented the first observational shallow cumuliform snowfall census on a global scale, using the CloudSat Cloud Profiling Radar. These studies show that there are specific regions at high latitudes where snowfall fraction and mean annual rate are high (30-50% of annual total precipitation fraction), e.g., between Canada and Greenland, over the north Atlantic region and north Pacific region, as well as over the Southern Ocean where 50-70% of solid precipitation can be attributed to shallow cumuliform events.

SCS events take place when cold air outbreaks interact with unfrozen large bodies of water and initiate convective processes in the boundary layer. The main characteristic of these systems is that they are very shallow, with cloud top heights typically between ~1 and 4 km. They also form in very dry ambient environmental conditions [2].

Another important study from Skofronick-Jackson et al. [4] compares CloudSat and the GPM precipitation products and shows that the GPM Dual-Frequency Precipitation Radar (DPR) generally underestimates precipitation occurrences and quantification when compared to CloudSat, while the GPM Microwave Imager (GMI) passive microwave (PMW) product, GPROF, generally observes higher snow occurrence and mean snowfall rate values than DPR. However, over the aforementioned oceanic regions the mean snowfall rates are largely underestimated. This underestimation is attributed to the contamination of the snowfall scattering signal by the radiatively cold ocean surface, enhanced by the dry conditions in which these events occur. Emission by supercooled cloud liquid water within these clouds may also dampen the ice scattering signal that precipitation algorithms heavily rely on to produce quantitative precipitation estimates.

Petty [5] presented a methodology to mitigate PMW limitations in detecting snowfall over ocean using the 89 GHz polarization signal. With a step further, Panegrossi et al. [6] highlighted the potential of the 166 GHz polarization signal, introduced with GMI, for snowfall retrievals. This work uses Petty's methodology [5] to mitigate GPROF limitations over ocean in detecting SCS in dry environmental conditions using the 166 GHz GMI channel.

2. CASE STUDY: 26 DECEMBER 2016

2.1. Overview

We analyzed a case study on 26 December 2016 over the ocean between Canada and Greenland. This region experiences a high occurrence of shallow cumuliform events [2]. The event shows a frontal system moving from northwest to southeast followed by an open cellular shallow convective region and a narrow linear cloud structure closer to the Canadian coast, also very shallow.

High frequency channels (≥ 89 GHz) are usually used in snowfall retrieval algorithms for their sensitivity to the precipitation layers, and polarization provides important information about the ice crystals within the clouds.

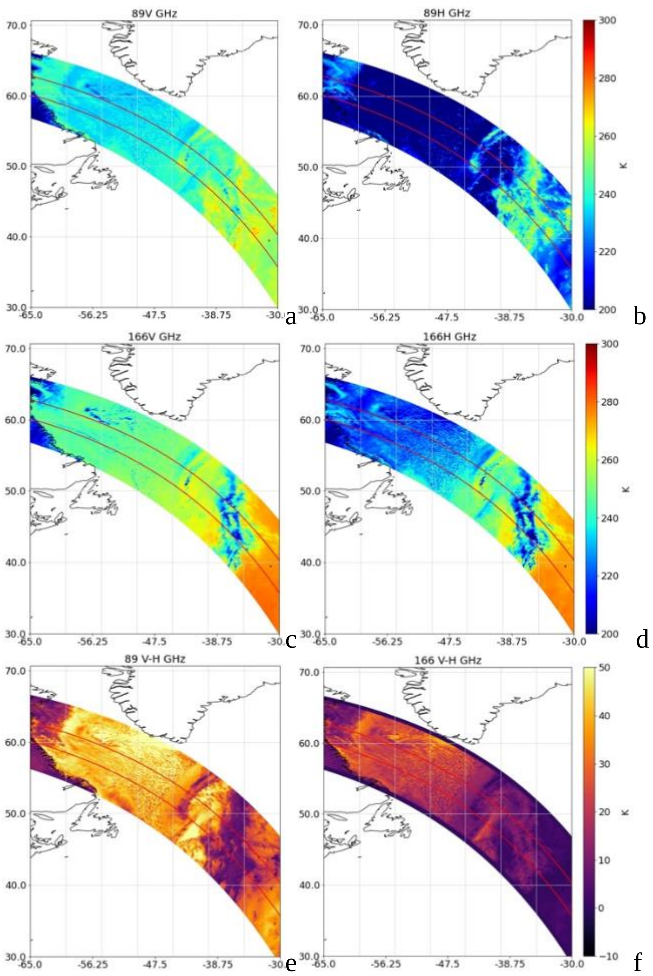

Fig.1. Brightness Temperatures maps from GMI orbit 016071 for the 26 Dec. 2016 case study. a) 89 GHz V-pol, b) 89 GHz H-pol, c) 166 GHz V-pol, d) 166 GHz H-pol, e) 89 GHz V-H, f) 166 GHz V-H.

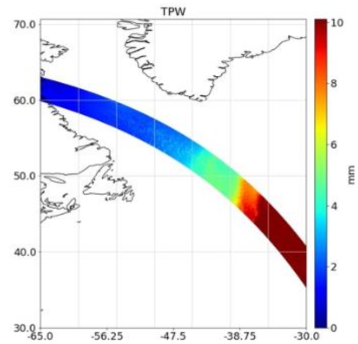

Fig. 2. Map of total precipitable water (TPW) from the Japan Meteorological Agency (JMA) Global Analysis (GANAL) product on 26 December 2016 for the GPM 016071 orbit. GANAL environmental variables are available within the GPM products.

Fig.1 shows 89 and 166 GHz brightness temperatures (TB) and polarization maps. The scene presents two very distinctive behavior, one for the deep frontal system clouds over the southeast portion of the orbit and the other for the shallow convective region over the north west part of the orbit.

At 89 GHz the deep frontal system is noticeable in the south-east (bottom right in Fig.1a,b) with increased TB values compared to the north-western region, likely due to the emission by the supercooled cloud liquid water often associated to precipitation events over ocean [7].

At 166 GHz the scattering by snow particles within the precipitating layers dampens the TBs from about 260 K of the surroundings to 220 K of the precipitating deep clouds.

Over the northern part of the orbit, the amount of water vapor is particularly low (Fig. 2), with values below 4 mm. In this case the signal received by the sensor originates from the surface, highlighting for both 89 and 166 GHz channels the very highly polarized water surface, while the SCS signal, whose presence is evidenced by the DPR (Fig. 3), is completely masked.

Panegrossi et al. [6] highlighted this issue very well. They used a regression tree method to analyze the 166 GHz polarization signal (i.e., the difference between V and H polarization channels) relationship to snowfall. They found that besides the surface type, which is the most impactful component in the polarization signal, the total precipitable water (TPW) is the second most important variable to take into account. Over ocean, in the presence of TPW below 5.1 mm, the 166 GHz polarization signal is very poorly correlated to snowfall.

For this specific case study, GPROF classifies precipitation as liquid over the southern portion of the orbit, corresponding to the deep frontal system, and solid over the northern portion, corresponding to the shallow convection (classification map not shown here).

The GPROF liquid precipitation pattern and quantification (Fig. 3a) is in good agreement with the DPR (Fig. 3b). In this region, TPW is well above 5 mm (Fig. 2, red region).

However, when considering solid precipitation (northwest portion of the orbit), GPROF provides a homogeneous precipitation pattern, as it confuses the cold, highly polarized surface signal with actual, very light precipitation (underestimated with respect to DPR) and does not detect the open cellular (shallow) convection that DPR recognizes. Over this region TPW is below 5 mm (Fig. 2, green/blue region).

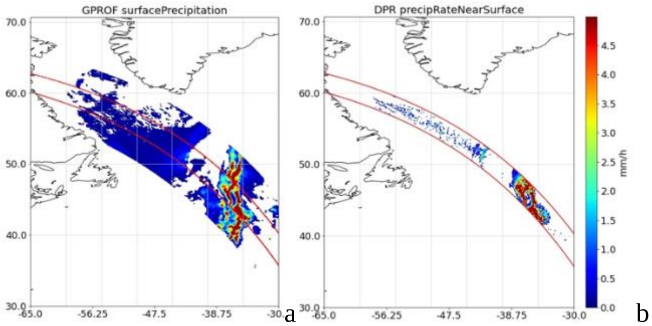

Fig.3. GPM precipitation rate products from a) GMI (GPROF product) and b) DPR, for orbit 016071 on 26 December 2016.

2.2. Scattering Index

In order to enhance the shallow snowfall signal over ocean for TPW below 5 mm we calculate the scattering index (SI, Eq.1). The SI, which was originally developed for 89 GHz observations in previous generation sensors [5], isolates the polarization signal from the surface and highlights only hydrometeor scattering effects.

$$SI = P \cdot T_{V,0} + (1 - P) \cdot T_C - T_V \qquad (1)$$

$$P = \frac{T_V - T_H}{T_{V,0} - T_{H,0}}$$

where T_V and T_H are respectively the all-sky vertically and horizontally polarized TBs, $T_{V,0}$ and $T_{H,0}$ the clear-sky polarized TBs and T_C is the saturated value set at 273K. The SI is calculated at 89 GHz (SI_{89}) and 166 (SI_{166}) GHz.

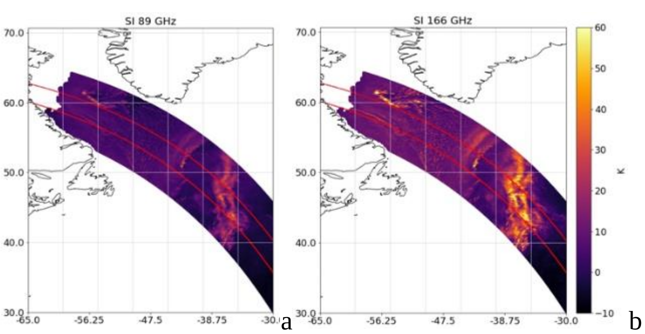

Fig. 4. a) SI_{89} and b) SI_{166} for the GPM orbit 016071 on 26 December 2016.

Both channels see similar features (Fig. 4), but SI_{166} shows a wider range of values and detects the open cellular convective clouds with a pattern very similar to the one shown by DPR (Fig. 3b). Over the northern portion of the orbit some narrow snow bands are also visible (parallel to the orbit). From the SI_{89} versus SI_{166} scatterplot (Fig. 5), it is clear that while the SI_{89} tends to saturate above 40, SI_{166} shows a wider range and provides more detailed information that highlights features not visible by SI_{89}. These results highlight not only the importance of the 166 GHz dual-polarization channels (available only with the GMI) but also the potential positive impact of using SI in PMW snowfall retrievals.

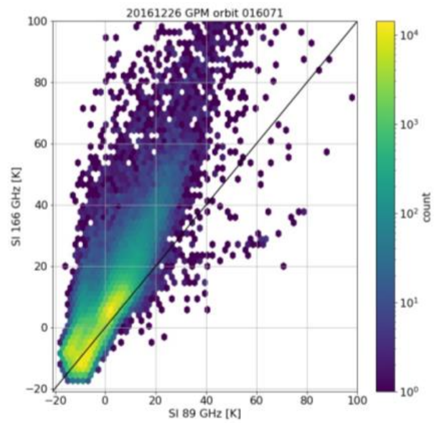

Fig.5. Density scatterplot of SI_{89} vs SI_{166} for GPM orbit 016071 on 26 December 2016.

The relationship between SI and DPR precipitation rates is highlighted by superimposing DPR precipitation rates on to GMI SI_{166} values (Fig. 6). DPR precipitation occurrence and intensity map remarkably well, even over the more challenging open cellular convection region associated with very dry conditions. In comparing the SI map (Fig. 5) to the 166 GHz V-H polarization signal (Fig. 1f), it is evident that the latter, analyzed in previous studies [7][8], provides a confused signal over the low TPW northern portion of the orbit, while the SI clearly follows the snowfall cellular pattern.

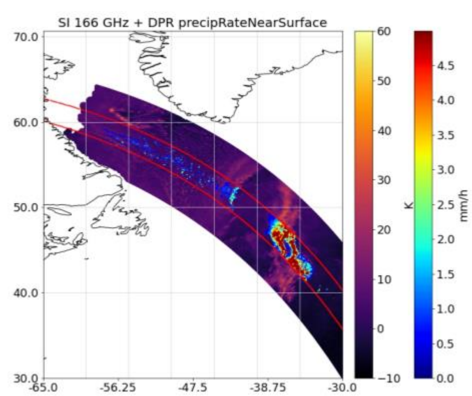

Fig. 6. Scattering Index at 166 GHz with the DPR precipitation rate superimposed.

2.3. Impact of Supercooled liquid water

The SI was applied to several similar case studies over different regions showing very similar results. However, the promising performance of this technique still exhibits some limitations. Over the northern portion of the analyzed orbit, above 60°N where the narrow snow bands develop, the SI detects the snowfall bands associated with the strongest scattering, but does not show all the other bands visible in visible and infrared images (not shown).

These kinds of shallow SCS events often contain a high content of supercooled liquid water within the clouds that can partially or completely mask the scattering signal.

DPR also shows some difficulties identifying precipitation, probably because of the low sensitivity of the sensor that cannot detect light snow. Extremely shallow snow bands may also be difficult to detect because of the ~1 to 2 km DPR blind zone located directly above the surface.

One of the next steps of this study will be to understand the sensitivity of the SI to the presence of supercooled liquid water and how this might affect SCS detection over ocean.

3. CONCLUSIONS

Solid precipitation over ocean represents a large percentage of total precipitation at high latitudes and shallow cumuliform snowfall is a large percentage of it. PMW have difficulties retrieving precipitation under specific environmental conditions (TPW < 5 mm) in which shallow cumuliform precipitation occurs, but the Scattering Index at 166 GHz (SI_{166}) can mitigate this gap. The SI pattern spatially matches the shallow snowfall pattern for the case studies investigated. The GMI SI_{166} is also much more sensitive to precipitation features compared to SI_{89}, the only high-frequency dual-polarization channel available before the advent of the GPM mission.

Future work will involve apply the SI to an extended GPM dataset and more closely study the impact of supercooled liquid water on SI and its sensitivity to snowfall. The potential on the use of SI in snowfall retrievals will be tested by implementing the SI into existing retrieval algorithms (i.e. GPROF) to improve detection and quantitative precipitation estimation of shallow snowfall over ocean.

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